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Physical Impacts of Marine Aggregate Dredging on Seabed Resources in Coastal Deposits

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ABSTRACT

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A detailed study of the seabed surrounding dredge pits created during the mining of marine aggregate from a small licence off the south coast of the United Kingdom ("Licence Area 122/3") has been completed. Over 350 km of high-resolution sidescan sonar imagery and 177 sediment samples have been obtained over a study area extending 10 km either side of the dredge zone (representing one full tidal excursion) in order to identify far-field effects on both physical and biological resources of the seabed.

The physical results presented here for Area 122/3 clearly show that the physical impact of dredging (without screening) on the seabed is limited to a zone within approximately 300 m downtide of the dredge area. This will generally be within the dredge licence boundary due to operational procedures. There is no evidence of suspended sediments falling to the seabed beyond this zone and causing significant changes, which may be manifested as infilling of small pits by fine sediments, siltation within crevices or development of migratory sand ripples. However, there is some statistical evidence from grab sampling that surface sediments have a greater sand fraction within the excursion track of the plume, than those sediments either side. Despite this small change in seabed particle size distribution, the benthic communities do not exhibit a detectable impact, as reported in the accompanying paper by NEWELL *et al.* (2002).

Analysis of ADCP backscatter data supports recent evidence for development of a near bed benthic boundary plume some 2–4 metres thick and a few tens of metres wide which extends beyond the limits of the dredge activity. On an extraction licence undertaking cargo screening, this near bed plume may exceed 4.5 kilometres downtide. Such a phenomenon provides a potential mechanism for impacting physical and benthic resources well beyond the dredge licence boundary and requires further investigation.

ADDITIONAL INDEX WORDS: *Aggregates, dredging, marine mining, benthic resources, environmental impact, dredge plume, sand and gravel, screening.*

INTRODUCTION

Marine aggregate mining in the United Kingdom for construction and fill purposes has averaged 23–28 million tonnes per annum over the past decade or so. In 2000, 23.05 million tonnes of sand and gravel aggregate was mined from an area of seabed amounting to some 179 km^2, out of an available licensed seabed of 1506 km^2, representing just 0.12% of the U.K. national seabed jurisdiction. Notably, over 90% of the activity took place within a total area of just 11.89 km^2. The 72 current licences in the UK have a permitted total extraction of 38 million tonnes per annum, with 30 additional licences presently in various stages of application.

Such an intensive resource-based activity will unavoidably have impacts on the environment. It is important, therefore, that the industry is regulated appropriately and, better still, adopts *Best Practices* to minimise and mitigate the impacts wherever possible. The United Kingdom has in place a competent, workable and sustainable licensing system to formulate and regulate the exploration and exploitation of the resources. This system is administered by the Department of Transport Local Government and the Regions (DTLR). Notwithstanding this, the industry itself has responsibly developed effective Codes of Practice and Initiatives to improve integration of their operations with those of other sea users.

Studies of the physical impacts due to dredging can broadly be grouped into those reporting evidence of seabed disturbances, such as DICKSON and LEE (1973) and PRICE *et al.* (1978), with little further work appearing until DAVIES and HITCHCOCK (1992); and those studies recently which have investigated the origins and fate of sediment plumes, a topic which has attracted considerable interest lately (see HAMMER *et al.,* 1993; LAND *et al.,* 1994; BONETTO, 1995; HITCHCOCK and DRUCKER, 1996; and HITCHCOCK *et al.,* 1998). The importance of sediment plumes cannot be underestimated as it is this phenomenon that has the capacity to extend the footprint of impact well beyond the limits of the dredging activity itself.

It is important to understand the operational modes of aggregate dredging. In its most simple form, sand and/or gravel mix is drawn by powerful pumps from the seabed to the

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dredge vessel along a suction pipe, the lower end of which is usually trailed slowly across the seabed. The dredged sand and gravel is retained 'all-in', regardless of cargo sediment size distribution, for discharge ashore. There is no 'processing' or 'beneficiation' of the materials dredged. A slight variation may be if the dredger is stationary or at anchor and the dredge pipe digs down in to the resource rather than trailing across. This is known as 'anchor' or 'static' dredging as opposed to 'trailer' dredging, and is commonly used for small, discrete resource areas or thick deposits.

More often, customers require a particular grade of aggregate, and it is economic to only load and transport the grade of aggregate required, rather than conduct grading operations at shore-side facilities. Most new dredgers therefore have the facility to 'screen out' unwanted fractions of the dredged mixture, returning the undersize (or oversize) sediments to the seabed. This process of screening can lead to many more times the actual cargo retained being dredged, with significant proportions returned immediately. NEWELL *et al.* (1998) notes 1.6–1.7 times the retained cargo is returned to the water column. This figure may be higher for particular cargoes, reaching 3–4 times the cargo load (HITCHCOCK and DRUCKER, 1996). Interestingly, the process can also foul the resource for the licence operator: continually screening and rejecting the finer sediments from the mixture, which are coarse enough to settle quickly under the vessel and therefore within the licence area, can lead to 'over-sanding' of the seabed, with subsequent coarse cargoes harder to load.

Within the dredged area, the persistence of physical impacts during and following dredging activities is a clear relationship between the nature of the substrate and the potential for natural disturbances that may infill the pits or scours formed by the activity. Shallower coastal deposits will be subject to greater natural disturbances than deeper offshore deposits. This has important implications for assessing the significance of likely impacts.

Pits within gravelly substrates have been observed variously to fill very slowly and persist after several years (DICKSON and LEE, 1973). VAN DER VEER *et al.* (1985) described recovery in the Dutch Wadden Sea. Pits in channels with high current velocities filled within one year, but those in intertidal watersheds took 5–10 years to fill.

Side-scan sonar records of dredge licences in coastal waters of the southern North Sea show that the seabed is crossed by a series of dredge tracks which are 2–3 metres wide and up to 0.5 metres deep (VAN MOORSEL and WAARDENBURG, 1990), although deeper troughs of up to 2 metres were recorded from where the dredge head had crossed the area several times. Similar results were observed in the English Channel and southern North Sea during detailed monitoring surveys (DAVIES and HITCHCOCK, 1992) and are discussed in more detail later. In high energy shallow water environments such as the dynamic sand banks of the Bristol Channel, dredge imprints are destroyed within a few tidal cycles.

Study Objectives

Our studies have examined the importance of the physical and biological impacts of marine aggregate dredging operations in the coastal waters of the United Kingdom. The results of the biological assessment are reported in NEWELL *et al.* (2002). Several key questions must be addressed:

(1) Does the use of ADCP techniques supported by traditional water sample characterisation still provide a best value approach to defining the gross morphology of the dispersing plume and any sub-divisions attributable to different sources and processes?

(2) Is there a detectable impact on the sedimentary provinces that may be caused by marine aggregate mining and is this significant?

(3) Can high resolution sidescan sonar mosaic imagery provide broadscale mapping at sufficient resolution to identify any impacts due to mining operations either due to changing sedimentary province and/or biological community?

(4) How far beyond the immediate limits of the dredged area do impacts extend?

(5) Can any impact on community structure beyond the boundaries of the dredged area be related to 'far-field' deposition of material in the outwash?

Study Site

Choice of a suitable study site presented some difficulties because the effects of the dredging process itself, important for the U.S. industry case, needed to be distinguished from secondary impacts through discharge of overboard screened material (which is not common in the U.S. at present). A complicating factor is that in many dredged sites, trailer dredging occurs over a relatively wide area and impacts may be dissipated in space and time and thus harder to detect.

A small intensively-exploited aggregate area to the east of the Isle of Wight, off the south coast of the U.K., known as the North Nab Production Licence Area 122/3 (Figure 1) is licensed to, and managed by, United Marine Dredging Ltd. This was selected as study site for a number of logical reasons:

(1) Although the amount of aggregates removed from the area is quite low, up to 150,000 tonnes per annum, material is extracted from very localised 'sweet spots', each of the order of a few hundred metres in diameter. This makes the operation one of the most intensively dredged sites per unit area in the U.K.

(2) The area was licensed in 1989 and has a good historical record of dredging activities, locations and volumes. Any impacts that may be created by the operations could reasonably be expected to be established by the time of the investigation.

(3) Although material is not screened (common in many U.K. operations, especially in the North Sea), 'all-in' loading is a feature of ¾ of south coast licences (A. BELLAMY, *pers. comm.*). It is also the predominant technique of loading cargoes in the U.S., although recent indications are that screening of cargoes at sea may become prevalent in the U.S. as well.

The North Nab study area is therefore representative of the majority of the Licence Areas on the south coast of the United Kingdom, in contrast with those of the southern North Sea which are generally heavily-screened and of lesser direct relevance to U.S. dredging practices.

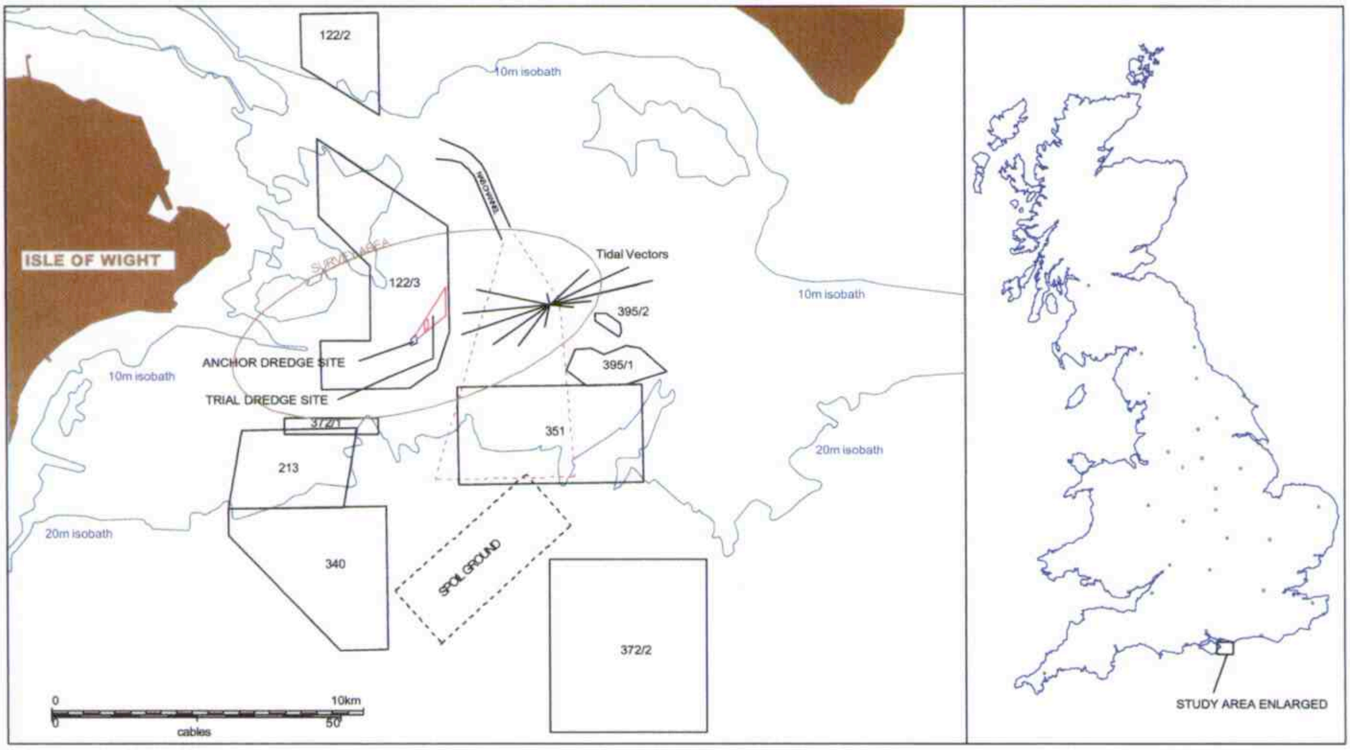

Figure 1. Study site location showing the study survey area and dredge licence North Nab 122/3 with small operating zones. Adjacent aggregate mining licences and spoil dumping ground are also outlined. Note the direction and magnitude of tidal vectors, the longest arrow equates to 1.8 kn (1.0 ms^{-1}).

The location of the study site and boundaries of the Licence Area are shown in Figure 1, together with the strength and direction of the tidal streams, broad boundaries of the area surveyed and the sampling stations. Within the boundaries of Licence Area 122/3, also shown are the sub-areas that have been exploited for gravel by different techniques (trailer suction dredging or anchor suction dredging) and for different times. Note also the presence of other dredge licence areas in the region, the nearest of which (Area 213) is some 4 nm to the SW of the active zone of 122/3. The spoil ground 4 nm to the SE of the study site is, for the purposes of this study, across tide, and is considered to have little bearing on the results. Other aggregate areas closer to the spoil ground will naturally have a more complex and cumulative effect which will blur the origin of effects due to dredging or dumping.

The different loading techniques practised at North Nab have provided unexpected benefits to the study objectives. Firstly, the presence of the two techniques in two distinct zones can be used to make a first assessment of the individual impact of each principal method of aggregate dredging on benthic biological communities, although it should be pointed out that less material is removed by trailer dredging than from the anchor-dredged site. Differences between the two dredging sites may therefore reflect dredging intensity, rather than the type of dredging method used. Secondly, the results also allow some comparisons of the nature of the recolonisation processes and rates of recovery in relation to anchor-dredging and trailer-dredging, as well as an assessment of the impact of the relatively small quantities of material discharged in the outwash for unscreened ('all-in') cargo loads.

Third, on a practical point, measurements of plume generation and decay originating from an anchored vessel are more straightforward to interpret using time-distance plots, due to the single source location. A trailing vessel will have a moving discharge zone that will compound the interpretation of the stage of plume development at any given point and hence time. Similarly, impacts observed at any point on the seabed will be compounded by the variable distance from the moving discharge point. This is important for determining not only the source terms for development of predictive models and assessments of impact for new extraction licences, but also for field validation of numerical models.

It is important to emphasise, however, that what is not included in this study is an assessment of the impact of the large quantities of material discharged as part of screening processes, common in other licence areas, as mentioned earlier. Similarly, the extent to which this quantity of material would affect sediment distribution, transport and sedimentation, or bed-form structure *etc.* is not known. Neither is it known how screening may alter the results of biological resources appraisal and rates of recolonisation reported in this project for the non-screening North Nab Licence Area 122/3.

Quite simply, analysis of the impacts of dredging a fully-screened cargo requires a comparative study at another site using the techniques of this project which have been proven in their principle and execution and which can be further refined in light of the observations made. The nature and rate of the recolonisation requires a specifically designed and systematic study that is co-ordinated with assessment of the differing dredge techniques and consequential plumes developed in a worked Licence Area.

MATERIALS AND METHODS

Survey Strategy

Six separate campaigns of data collection investigating the far field and then near field effects of dredging activities have been completed at the North Nab study site. Four other campaigns were aborted due to weather conditions and on one occasion due to damage to the dredger whilst on passage to the study site. Horizontal control of the survey was accomplished using a survey quality dGPS comprising a Trimble 4000SSi for primary positioning interfaced to a SeaSTAR differential corrections receiver. Layback to remote sensors such as the sidescan sonar fish or the grab sampler was established using measured offsets, vessel track and a TSS Meridian gyrocompass. Survey control was provided by the Integrated Navigation System developed by Coastline Surveys Limited and using the Trimble HYDROPRO navigation package.

Some 177 grab samples were obtained over 4 phases of the work using a standard 0.2 m^2 Hamon-type grab, deployed from the 23.3 metre survey vessel *MV FlatHolm*. Most of these samples were analysed for benthic community (see HITCHCOCK *et al.*, 2002b). Grain size analysis of the fractions 0.075 mm–125 mm by sieving determined the principal components of the seabed sediments (according to BS1377 and BS812: Part 102). Similarity analysis of the sediment size distributions was performed using standard non-parametric multivariate analysis methods.

Sidescan sonar imagery was obtained using a high quality GeoAcoustics Dual frequency 100/400 kHz towfish integrated to a GeoPRO sidescan mosaicing processing system. Sonography was recorded digitally on the mosaic system and concurrent high quality hard copy printed on an Ultra 200 three-channel thermal recorder. Trigger time and scan width was set at 333 and 67 milliseconds per channel depending on transmit frequency. The real-time facilities of this system enabled full coverage of the seabed to be confirmed whilst on site and promoted the accurate positioning of seabed calibration samples in zones of different seabed reflectivity.

The bathymetry of the survey area was established during each survey using a standard survey spread comprising a high-resolution single channel 208 kHz echosounder interfaced to a Seatex MRU-5 multi-reference motion sensor. Seabed levels were reduced to Chart Datum using recorded tides.

The survey zone was determined by pre-analysis of the dredge history of the site and assessment of tidal movements within the region. Tidal excursion on spring and neap tides is given by a local tidal diamond at 50° 40.1′N, 000° 56.3′W, some 1200 m to the east of the dredge site centre. Tidal streams reach up to 1.0 ms^{-1} on the flood (078°) but only 0.8 ms^{-1} on the ebb (252°). Maximum tidal excursion is slightly less than 13 km to the east and west. Based on the information obtained in previous studies on an area some 20 km to the east, we therefore designed the survey and sampling regime to extend up to 6 km in each direction, with the axis of the investigation aligned with the tidal excursion. The width of the survey area was delimited to 1000 m.

As mentioned earlier, comprehension of plume morphology formed by dredging activity at each site is fundamental in assessing any impacts of dredging beyond the limits of physical disturbance by the dredge head. It is primarily by this mechanism that any impacts will be extended beyond the active dredge zone. Over the past decade, we have developed in the U.K. novel techniques for tracking development and decay of marine dredging plumes using a combination of the latest ADCP systems and traditional water sampling techniques. These practices are now common worldwide. New advances in software analysis and presentation enable hitherto unknown representation of plume structure.

The form and magnitude of the plume is governed by three principal components;

(1) the dredging technique, including type of dredging plant in operation, method of overboard returns, and operational conditions such as speed over the ground;

(2) sensitivity to suspension and resuspension of the bed material *i.e.* the ease with which the bed material will be disturbed and will remain in suspension, largely determined by the characteristics of the sediment (geotechnical, rheological and micro-biological);

(3) condition of the overlying waters *i.e.* water depth, current velocity and shear, turbulence, temperature, wave climate, salinity *etc.*

A full description of ADCP systems procedures is outwith the scope of this paper, but see THEVENOT and JOHNSON (1994), LAND *et al.* (1994) and HITCHCOCK *et al.* (1998). The utility of ADCP techniques as interdisciplinary instruments for mapping sediment plumes are now well established and accepted.

Data Collection

Six field campaigns were undertaken. During March and June 1999 141 seabed samples were obtained over the entire area, including some repeat stations. In September 1999, a further 10 samples were obtained close into the dredge site, as it became apparent that the effects were much more limited in proximity to the dredging activity itself and, more than likely, located primarily within a few hundred metres of the active zone. In August 2000, a further 10 samples were obtained from within the active zone again, during an opportune effort to make a preliminary assessment of the expected rate of recovery.

Some 350 kilometres of high resolution sidescan sonar and bathymetry has been processed. These have allowed us to create high quality fully orthorectified digital mosaics of the seabed, over which discriminators of the footprints of impact of the dredging operation can be laid for further analysis.

The sediment plume generated by a small suction dredger, the *City of Chichester*, was monitored by ADCP techniques during the loading of an 'all-in' cargo. An RDI 1200 kHz

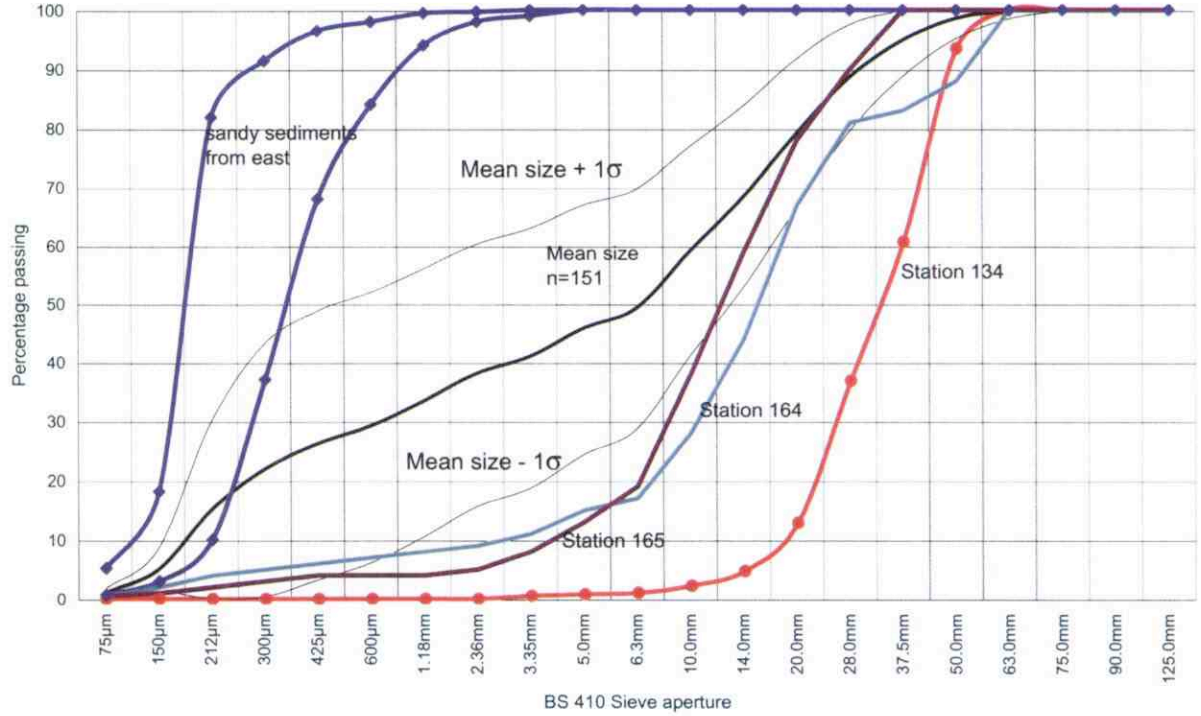

Figure 2. Mean particle size distribution and variance (1 sigma) for 151 samples obtained from the study site. The predominantly sand sized curves on the left were obtained from the eastern end of the study site and reflect a generally sandy seabed. The three curves to the right (stations 134, 164 and 165) were obtained from the actively dredged pits and show presence of very well sorted coarse gravels.

BroadBand unit was deployed over the bow of the survey vessel and the equipment and software configured for moving vessel mode. ADCP transects across the plume were conducted at differing ranges from the anchored dredge vessel, to determine the plume shape and morphology. Two distinct monitoring strategies were followed. In the first, the survey vessel conducted transverse profiles perpendicular to the plume axis at set distances downstream of the dredge vessel, and produced a series of profiles indicative of the status of the plume and its dispersing morphology. Water samples taken at varying points along each transect and at different depths give sediment mass per litre of seawater (suspended sediment concentration). The samples were too small for grading. Each of these profiles represents a time-dependent status of the plume, and the rate of dispersion and settlement of the sediments can be determined.

Secondly, the survey vessel deployed a mid-water drogue with a surface buoy in the plume just downstream of the dredge vessel. The survey vessel then conducted vertical and transverse profiling away from the dredger, always passing through the same parcel of water as indicated by the drogue surface buoy. This technique gives a time-based status of the plume but also removes some of the variability of the loading process and the 'pulsing' of overboard spilling of sediments from the dredge vessel. Specifically, within this study, we have not attempted to calibrate the ADCP backscatter signals with particular suspended sediment concentrations.

RESULTS

Granulometry

The deposits exposed within the centre of survey area generally comprise >50–60% gravels, this is the zone of active dredging and is clearly the material for which the licence was chosen. Figure 2 summarises the particle size distribution curves for the samples obtained (n = 151). Generally, the sediments are sandy gravels or gravelly sands. There is a clear subset of samples which are predominantly sand, where gravel content falls to less than 5%: these are located to the east of the survey area. To the west of the licence area, gravel content falls to less than 40% and there is an increase in silt content. Within the licence area grain size d_{50} ranges 6–12 mm: to the west this reduces to 4–8 mm and to the east reduces 1–2 mm. From Figure 2, the distinct sample stations 134, 164 and 165 are located within the dredge pit, and reflect a coarse gravelly deposit, which is the target resource. Silt content is generally less than 1–3%, with highest levels in the extreme west boundary of the study area, away from the dredge zone.

Figure 3 shows the boundaries of the principal sediment provinces based on multivariate analysis of the sediment classes, overlain onto the regional sidescan sonar mosaic of the region collected in 1999. The major sediment provinces are well indicated by the production licence area that closely follows the distribution of gravelly sediments. This supports

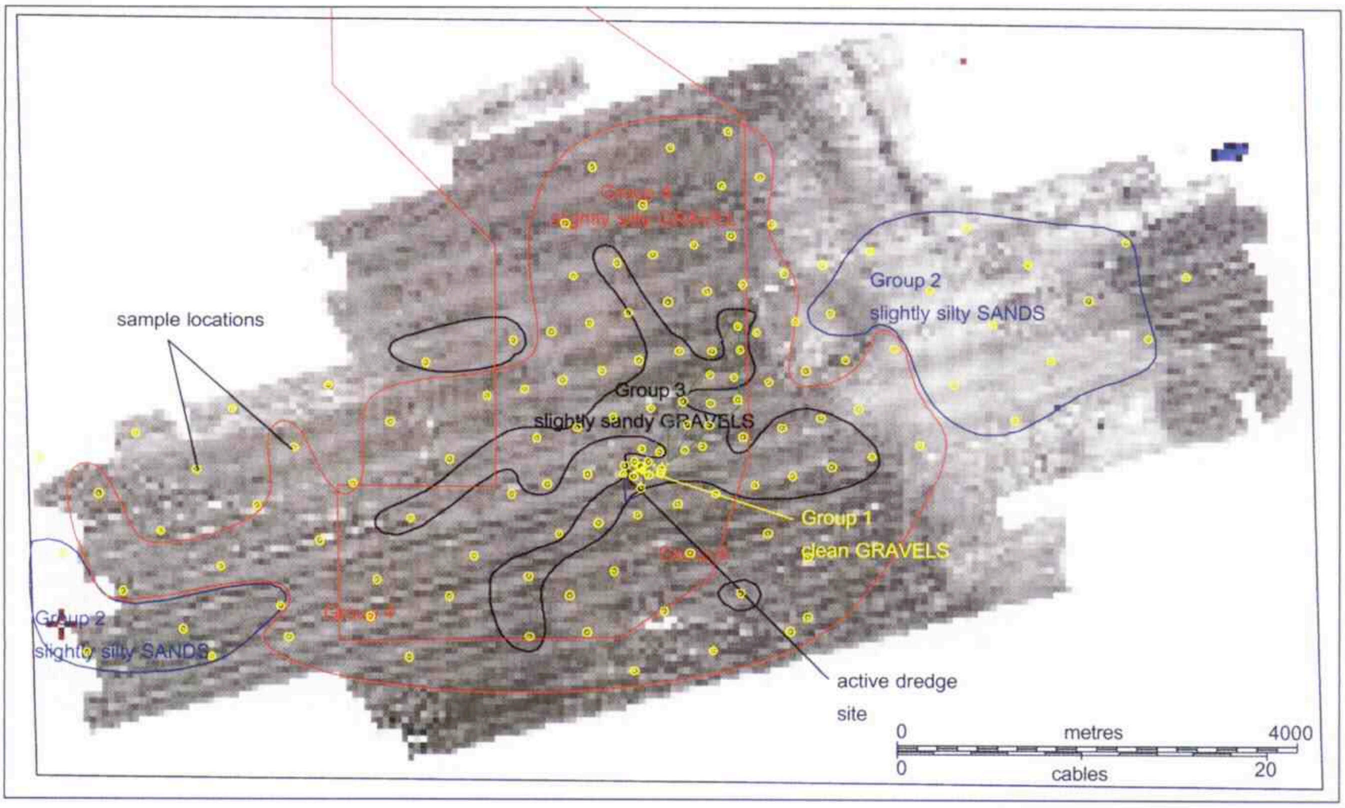

Figure 3. Sidescan sonar mosaic of the Area 122/3 study site with principal sediment provinces superimposed on the sonargraph. The correlation between sandy sediments and low reflectivity is clear to the east of the mosaic. Other than the exposed sub-bottom sediments of Group 1 (clean gravels), almost the entire licence area consists of slightly silty gravels. Note the elongated changes in sedimentary composition (Group 3) adjacent to the dredge zone aligned with the principal tidal vectors, to the South West, West, North and East.

the resource management Voluntary Initiative to restrict licensed areas of the seabed to the minimum required. These techniques enable a detailed assessment of the sediment distribution, and importantly reveal small groups of gravelly sediments that show an elevated sand content, distributed around the actively dredged area, not discernible by other geostatistical techniques. The zones of sandier gravels extend some 1500–2000 m away from the dredge location and correspond well with the predominant tidal axes away from the active dredge zone. These may be a result of geological conditions or more likely a result of dredging disturbances.

Sidescan Sonar Imagery

Inspection of the sidescan sonar mosaic presented in Figure 3 clearly shows the differing acoustic contrasts of the seabed in the principal sediment provinces. To the east, the lighter tone reflects the distribution of predominantly sandy size sediments. The remainder of the survey area is typically a uniform dark grey, characteristic of even, coarser sediments. The distribution of coarse sediments on the sonargraphs is again quite clearly matched by the licence boundaries. Other than a very small zone, some 500 m^2, on the extreme northwest boundary of the survey zone, there are no bedforms such ripples or megaripples. This localised development is near a small shelf of local solid exposure. Around the actively dredged area there is no evidence of development of sand ripples or other microtopographical features indicative of a localised sand transport path, as may be expected to develop during overboard release of sediments. We know that screening does not occur on this licence, so the potential quantity of remobilised fine sediments is small.

Anchor dredge activity can clearly be located on the sidescan sonar. Single dredge pits caused during isolated test dredging operations are also clear around the main dredge area. There is also localised evidence of trailer dredging activities in the designated zone, but these trails are poorly distinguished. Loading whilst trailing is not commonly undertaken. Anecdotal evidence from the vessels suggest that the method performs poorly in this locale, due possibly to presence of a lag gravel deposit through which the dredge head does not penetrate easily. Measurements from the sonographs indicate that the trailer dredge tracks are shallow, some 10–20 centimetres deep. Width is poorly distinguished.

Sediment Plumes

A composite image of the continuous backscatter profiling (CBP) of the plume developed by the 2300 tonne capacity *City of Chichester* during loading of an all-in cargo is shown in

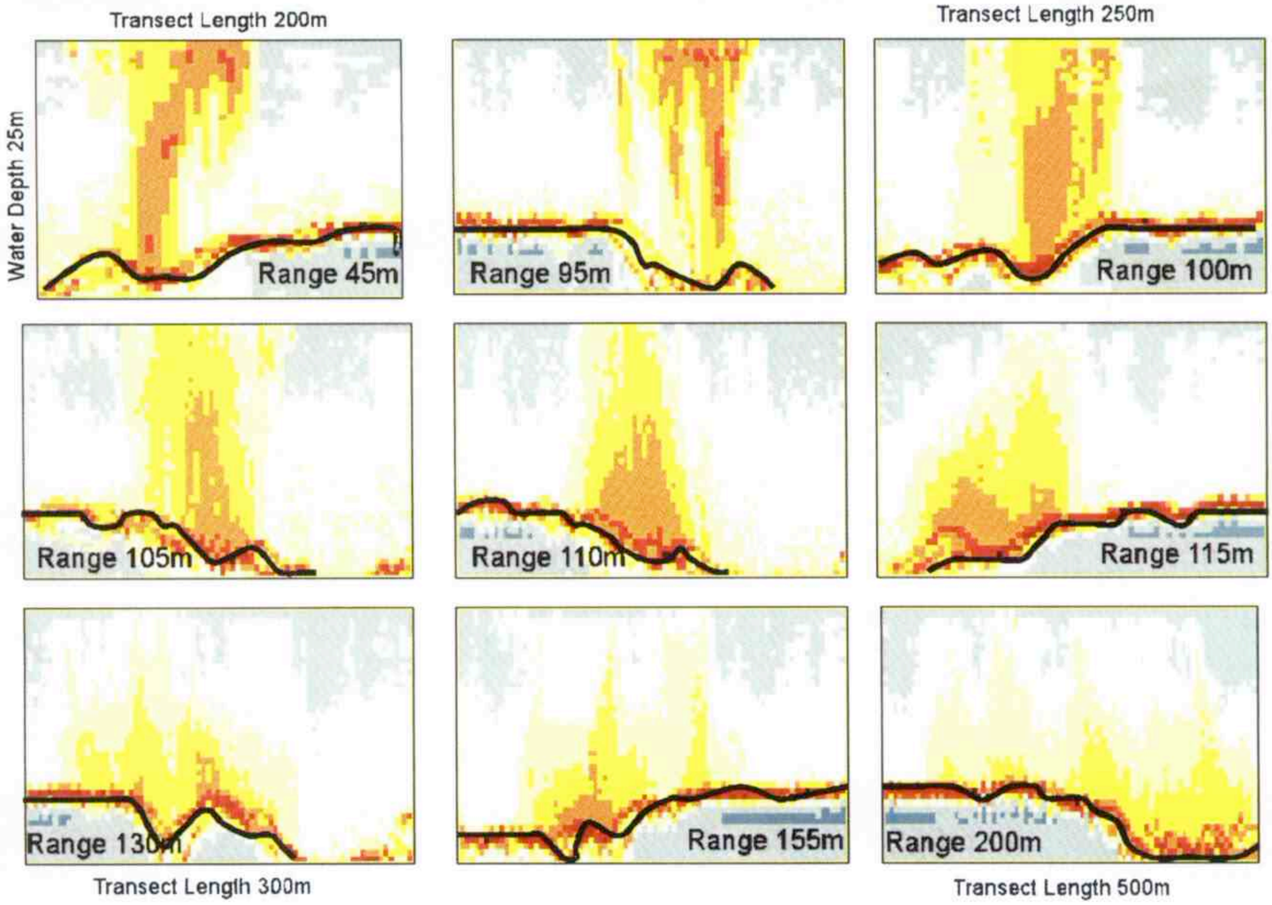

Figure 4. Series of Acoustic Doppler Current Profiles obtained with a 1200 kHz RDI BroadBand system astern of the 2300 tonne capacity suction dredger City of Chichester whilst loading at anchor without screening on Licence 122/3. Profiles show high intensity backscatter (red) close to and immediately astern of the dredger, reducing quickly to levels approaching background away from the dredger.

Figure 4. The screen-dump images show a series of transects downstream of the dredger at varying distances. Data collection at the far-field extremes of the survey, necessary to prove return distances to background levels, was curtailed by the presence of numerous small vessels at anchor. Nevertheless, the transects and samples obtained give a good indication of the near-field density current dynamic phase plume morphology. High intensity backscatter values are coloured red, reducing through yellow, white and to pale blue approaching background levels of backscatter. Close to the dredger, the plume can be visualised falling immediately below the vessel (45 metre image). The sequence 45 metres to 200 metres shows the dense plume falling to the seabed, and spreading laterally downstream of the operation. Scale of the transects changes with range from the dredge, such that the 45 metre transect is some 200 metres wide, whilst the 200 metre transect is some 500 metres wide.

Suspended sediment samples obtained by subsurface pumps immediately astern of the dredger are presented in Table 1 along with corresponding depths and distances downstream of the dredger. Pre-dredging background levels are 5–10 mg/l in settled conditions. Maximum values reached are approximately 5.5 g/l reducing to 450 mg/l further away from the vessel at the limit of the survey. Considerably more samples are needed for future works to resolve the fine scale eddies and internal structures that are developed during the overspill process. Included in Table 1 are corresponding results of a previous study on an adjacent site, using a similar methodology. In this instance, generally much lower concentrations of suspended sediments were recorded. Although the vessels are similar in size and operation, this may be due to different tidal conditions in the earlier study leading to much quicker dispersion of the plume. VAN DER VEER *et al.* (1985) measured overflow concentrations of suspended sediment from a small dredger to be 6300 mg/l, within range of the results obtained here. Background concentrations were found to average 60 mg/l.

Sampling data from our 1995 research (HITCHCOCK and DEARNALEY, 1995) indicated that at distances less than 100 metres from the dredger, total suspended solids concentrations ranged 480–611 mg/l in the lower water column, and 80–340 mg/l in the upper water column. Most of the sand had settled out reaching background levels within 250 metres, implying a forced settling rate of 32 mm/s in the water depths

Table 1. *Table showing the total suspended sediment concentrations in waters downstream of aggregate dredging operations on two English Channel sites (*Nab *and* OWERS*). Ten litre samples obtained using sub-surface pumps.*

Sample Number	Distance Downstream (metres)	Depth (metres)	Sample Volume (litres)	Suspended Solids (mg/l)
NAB18	65	2	8.54	1030.445
NAB23	66	5	7.594	5517.514
NAB14	84	18	9.049	1259.808
OWERS20	94	4		723
NAB24	98	2	7.367	1615.312
NAB31	109	2	6.9	695.6522
OWERS21	111	8		103
NAB19	133	5	9.298	1312.11
OWERS01	138	12		1170
NAB15	152	15	8.926	728.2097
OWERS02	156	16		1171
OWERS03	178	18		1346
NAB32	183	5	7.439	927.544
NAB20	192	10	8.595	1407.795
OWERS04	194	18		1225
NAB25	195	10	7.724	1993.786
OWERS16	201	4		47
NAB16	210	10	8.651	947.8673
OWERS17	227	8		304
OWERS18	248	12		582
NAB21	258	15	8.694	1702.323
OWERS19	259	18		613
NAB26	262	18	7.785	3301.22
NAB33	272	10	8.021	411.42
NAB22	331	18	8.363	442.425
NAB17	337	2	4.965	2819.738
NAB34	350	15	9.171	621.5244
NAB27	474	5	7.899	696.2907
OWERS10	491	1		46
OWERS08	534	18		18
OWERS09	549	18		22
OWERS07	561	16		18
OWERS06	573	12		18
OWERS05	585	8		26
NAB28	612	10	7.277	3091.933
NAB29	674	15	8.288	711.8726
OWERS11	675	4		10
OWERS12	691	8		13
OWERS13	707	12		13
OWERS14	724	18		25
OWERS15	740	18		38
NAB30	776	2	8.126	615.3089

and current speed encountered, whilst the silt content reached background within 480 metres implying a settling velocity of 17 mm/s. This study provides suspended solids concentrations an order of magnitude higher, in the range 0.5–5.5 g/l.

Figure 5 records two longitudinal profiles downstream of the dredging operation to the limits that were possible on the day. The first profile (45 metres to 820 metres) shows a reduction in backscatter with two distinct phases. At about 300 metres, there is a rapid reduction in suspended solids backscatter. It is not clear whether this is a phenomenon of irregular loading and hence discharge rates (the dredge density and rate varies by the minute), or may represent observations similar to previous work, with a major reduction in the plume density roughly 300 metres to 500 metres from the dredge site (NEWELL *et al.*, 1998; HITCHCOCK and DRUCKER, 1996).

Interestingly the second profile shows a near bed extension to the dense plume, extending beyond 800 metres, some 3–4 metres high in the water column off the seabed. This is important because it gives us, for the first time, some indication of a near bed extension to the benthic plume that has been observed by others (DICKSON and REES, 1998) and is discussed further in the following sections.

DISCUSSION

Impact Outside The Dredge Boundary

New software developed in this project has enabled us to re-process data collected in previous research and presented elsewhere (HITCHCOCK and DRUCKER, 1996). Figure 6 presents a 3D image of the 1996 plume data collected on the Owers Bank aggregate licences, some 25km to the east of the Nab study site. This re-processing has enabled us to identify a near bed extension to the dense dynamic phase of the plume that extends beyond the zone of monitoring, and hence well beyond the zone of previous detected impacts outside the dredge boundary. In water depths of 21 metres and currents of up 3 ms^{-1}, extraction of sand and gravels with screening would appear to generate a near-bed plume, some 2–4 metres thick, that extends downstream beyond 4.5 kilometres from the dredge site. The fate of the material is presently unknown since data does not exist beyond this zone.

However, the recent study by DICKSON and REES (1998) does suggest that benthic landers have monitored the progress of a near bed plume of sediments some 8 kilometres from a dredge site in the southern North Sea, although the dynamics are still to be fully resolved. This observation is important for two reasons: (i) using different technologies, independent studies have corroborated the presence of a near bed plume extending some way beyond the dredge site; and (ii) the extension of the near bed plume beyond the dredge zones gives credence to a mechanism for faunal community enhancement that has been observed in various studies (NEWELL *et al.*, 1998; POINER and KENNEDY, 1984).

It has often been assumed for the purposes of simulation models for British coastal waters that the dispersion of material rejected *via* the reject chute and spillways during the dredging process is controlled by *Gaussian* diffusion principles. Consequently, tidal currents could carry suspended material as much as 20 kilometres each side from a point source of discharge. Indeed, in water depths up to 25 metres and peak spring tide velocities of 1.75 ms^{-1}, very fine sand may *potentially* travel up to 11 kilometres from the dredging site, fine sand up to 5 kilometres, medium sand up to 1 kilometre and coarse sand less than 50 metres. In current regimes with a lower peak velocity of some 0.9 ms^{-1}, similar sized material may only travel up to 6.5 kilometres from the point of release (HR WALLINGFORD, 1993). Worst-case estimates have suggested that sediment plumes may persist for up to 4–5 tidal cycles.

Interestingly, detailed and extensive monitoring campaigns associated with the construction of the Storebælt Link have detected suspended sediment related to a specific dredg-

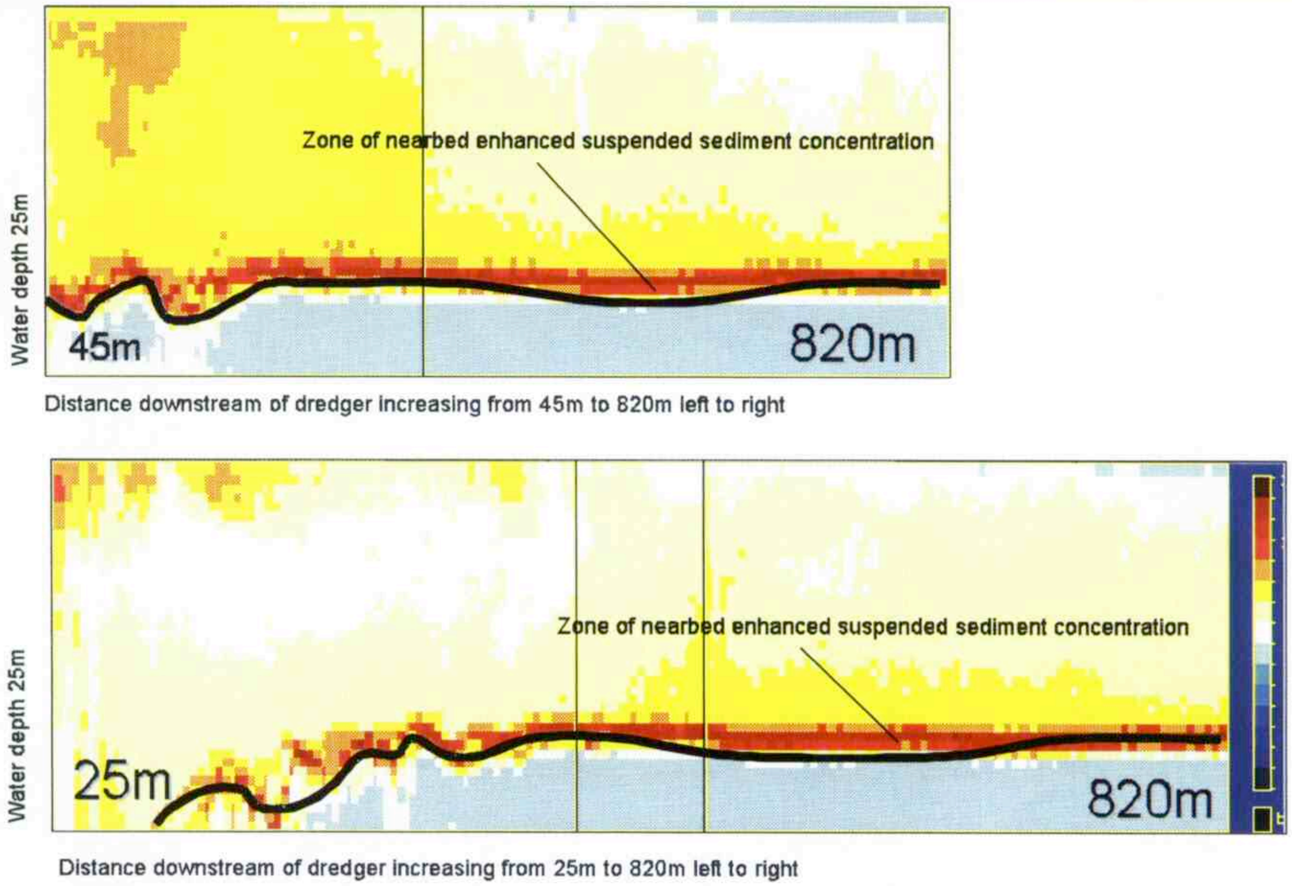

Figure 5. Backscatter profiles obtained downstream of the City of Chichester at Area 122/3 showing the persistence of the nearbed sediment plume to the limit of the monitoring area. Higher suspended solids concentrations (note possibly also includes air bubbles) are shown in the darker colours. The black line represents the seabed. Clear waters appear in light blue. The 45m range transect shows an asymmetrical plume representing greater discharge from one side of the vessel than the other (due to vessel trim noted during survey). The 95 m transect shows the plume as two distinct components, issuing from spillways either side of the vessel. Transects further away from the dredge vessel depict the higher concentrations of the plume body sinking closer to the seabed with distance downstream.

ing operation up to 35 kilometres from the source. However simulations have shown that 6 kilometres from the operations, the 'monthly average surplus suspended solids concentrations' caused by some of the most intensive dredging operations were at the same level as the background concentration (2 mg/l).

Investigations in Hong Kong were undertaken at an early stage when marine dredging for aggregate was considered (HOLMES, 1988; WHITESIDE *et al.*, 1995). The concern for plume impingement on sensitive spawning grounds necessitated monitoring of water quality during dredging operations. The investigations concluded that within the water column the practical effects of enhanced suspended solids concentrations are difficult, if not impossible to assess. The effects were observed to be short lived and of limited areal extent and therefore concluded that suspended sediment impacts within the water column were negligible, away from spawning and mariculture zones, even though *in situ* fines contents were significant.

Further, and probably related to the sampling methodology and dredging technique, suspended solids concentrations in the hopper surface waters were only 10000–30000 mg/l, reducing rapidly to 5000 mg/l adjacent to the dredge vessel in the sea. A rapid dilution is therefore observed. HOLMES (1988) observed that (1) the sand fraction settled quickly within a few hundred metres of the dredger (at a rate of 46mms^{-1} for 320 micron particles); and (2) the pelitic fines content will settle much slower at 0.1–1 mms^{-1} and will therefore disperse over a wider area, observed up to 4 kilometres. KIØRBOE and MØHLENBERG (1981) monitored the operation of a sand suction dredge in the Øresund, Denmark and concluded that any suspended solids concentrations likely to be detrimental were not present more than 150 metres downstream of the dredge. Levels adjacent to the dredge were up to 5000 mg/l, rapidly decreasing to 100 mg/l at 150 metres. Background levels were regained at 1000 metres downstream.

A plume dispersion model developed by WHITESIDE *et al.* (1995) for the surface layer (the upper 8 metres of the water column) for up to 40 minutes after discharge compares well

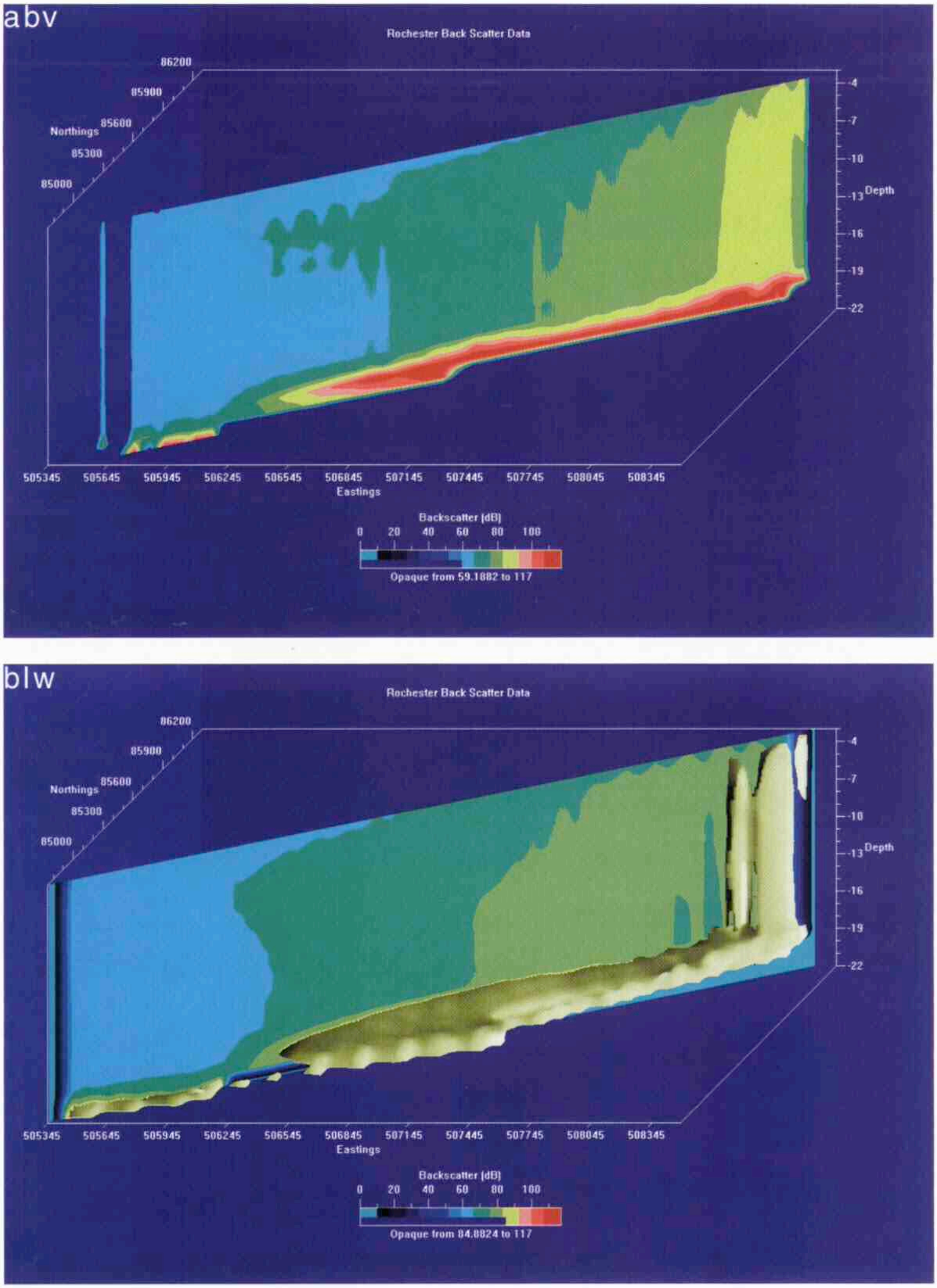

Figure 6. With newly developed software, backscatter profiles obtained in 1995 during screening operations on a deeper, more intensive and extensive aggregate licence located 25 km to the east have been reprocessed and reveal the presence of a noticeable nearbed sediment plume extending well beyond the initial zones of impact.

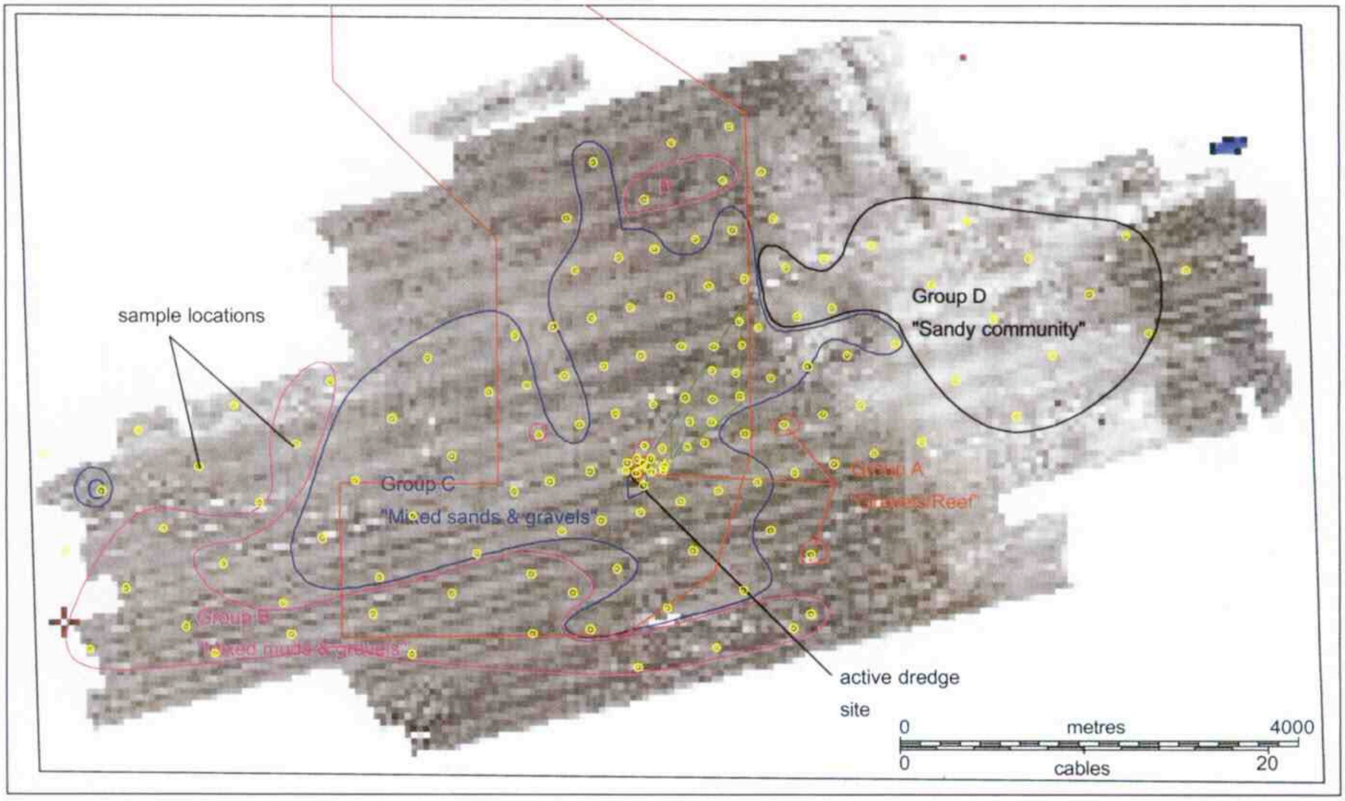

Figure 7. Superimposing the benthic community types on the sidescan mosaic and comparing with Figure 3, we can see that there is no correlating change in community type similar to the recorded changes in sediment province. Community Groups B and C pass over the tongues of sandy material downstream of the dredge zone (this does not appear to be an artifact caused by data density).

with plume decay measurements in the vicinity of the dredger. The contours for sediment deposition evidently remain as a narrow band extending for approximately 100 metres on each side of the track of the dredging vessel, much as recorded by GAJEWSKI and USCINOWICZ (1993) for Baltic waters.

Impact within the Dredge Boundary

There is little data worldwide to compare with the results of this study unlike the impacts beyond the dredge zone discussed above. Processing of the Nab ADCP data has produced an image of the plume that confirms the presence of a near bed plume extension mentioned elsewhere. This plume has the capacity to egress the 10 metre deep hole dredged below the level of the surrounding seabed. The limits of the plume extension may however, be limited by the flux of sediment available to contribute to the plume and also the limited time available for the plume excursion. An important operational feature of the Nab 122/3 licence is that exploitation commonly takes place for around an hour either side of low water, this being the expedient time for the vessel to return to port to discharge in the tidal berths found locally. This has important implications for the potential for plume dispersal, in that many dredging operations will not take place during peak tidal flows, but only in those weaker flows a few hours either side of low water.

Sediment Composition

Figures 3 & 7 clearly show the distribution of sediments (as discussed earlier) and faunal communities. For a detailed analysis of the benthic resources, see the accompanying paper by NEWELL *et al.* (2002). Importantly, the lack of correlation between the change in sediment type downstream of the dredging activity (the enhanced 'sandiness' of the gravels) and the faunal community suggests that either the type of community structure present is unaffected by the change in sediment composition or, more likely, is tolerant of the level of change that the community has been exposed to. However, an increased or prolonged exposure may cause a negative impact, or the existing exposure may cause a level of stress to the community that reduces its tolerance to other impacts, leading to the potential for 'cumulative' impacts.

Seabed Configuration

The most striking changes within the dredge boundary are produced by the dredging activity itself (Table 2). Anchor dredging produces the largest single features, with seabed pits reported by DICKSON and LEE (1973) some 4 metres deep by 50 metres diameter, whilst we have reported here bed levels up to 10 metres below the surrounding deposits, the base of the depression having dimensions of 300 metres × 100

Table 2. *Comparison of potential impacts according to the type of mining method.*

Type of Dredging	Advantages	Disadvantages
Deep isolated pits	impact on small area reduced or little modification of wave and current patterns	entrapment of bed load irregular, hummocky terrain increased possibility of disturbance of underlying strata e.g. clays seabed topography unsuitable for trawling stratification of water within deep pits possibility of anaerobic conditions in deepest pits reduced chances of faunal recovery
Shallow extensive furrows	reduced alteration of topography improved conditions for faunal recovery reduced possibility of exposure of underlying strata suitability for modern dredgers	may effect current and wave patterns extensive area impacted

metres. The fisheries concerns against this type of dredging methodology centre on the risk of snagging towed gear within the depression, and general unsuitability for beam trawling. Deep pits may also pose the risk of formation of an anoxic bottom layer of water with reduction of water circulation and accretion of fine sediments in certain hydrodynamic conditions, predominantly 'low energy'. However, our deployment of an underwater camera in the pits at the Nab 122/3 licence recorded little visual difference to water turbidity of the surrounding natural bed levels, whilst a similar number of individual fish and other benthic dwellers were observed.

ÅKER, HÄKKINEN and WINTERHALTER (1990) report that turbid waters could not be detected further than 'a few hundred meters' down current from the dredger. Normal water quality variations caused by current activity and storm suspension were found by them to be greater than that caused by sand extraction, although no values are given. They also consider that the operation had no 'clearly detectable' effect on fishing in the general area.

Trailer dredging produces a 'furrowed' topography and has been observed by DICKSON and LEE (1973), and more recently analysed in detail by DAVIES and HITCHCOCK (1992). Different types of dredge imprint are reported in the latter work. The dredge imprint will vary according to the type of draghead used, but some features more generally associated with one particular type of draghead can occasionally be found on others. Importantly, however, the furrow width is generally less than approximately 1 metre greater than the width of the draghead. Narrower dragheads produce deeper furrows, approximately 2.5 metres width by 0.5 metres deep. Wider dragheads such as the 'California Type' produce shallower and wider furrows 0.35 metres deep by 3.5 metres wide. Recently, some companies using the simple 'Fixed Visor' type of draghead have replaced them with California Type dragheads with significant improvements in the quality of cargoes loaded and simultaneous reduction in the loading times. DÉSPREZ and DUHAMEL (1993) report sidescan sonar observations of dredge furrows on the Klaverbank being 3 metre wide and approximately 0.5 metre deep. KENNY and REES (1996) observed furrows 0.3–0.5 metres deep but only 1–2 metres wide: however it is known that the furrows were made with a 'California Type' draghead of some 2.6 metres wide. One year after dredging, the furrows were no longer distinguishable by underwater camera, whilst after 2 years the furrows were barely detectable by sidescan sonar. ICES (1975) concede that trailer dredging does not greatly affect the action of seabed trawls. There has been little data put forward since to change this statement.

DAVIES and HITCHCOCK (1992) noted that many furrows were characterised by the formation of lateral *levées,* resulting from the draghead digging deeper into the seabed than the pumps could remove. This is an inefficiency in the system, and it is apparent that the wider dragheads do not suffer from such losses as much as the narrower types. There is thus less potential for interference with trawling activities.

Changes in composition of the seabed sediments may cause changes to the benthic community structure. DÉSPREZ and DUHAMEL (1993) noted that following intense dredging activity off Dieppe, the predominantly sandy gravel surface sediments were reduced to predominantly sandy sediments (possibly existing as a thin veneer of mobile sands deposited by the settling overboard returns). Further, they recorded dominance of several new species characteristic of finer sediments with establishment of communities of the Polychaetes *Ophelia acuminata, Nephtys sp.* and *Spiophanes bombyx* and the Echinoderm *Echinocardium cordatum.* These species were also observed in the sandy sediments present on the Klaverbank although in this case extensive rather than intensive dredging did not lead to distinguishable changes in predominant sediment grain size. A detailed assessment of the implications to benthic communities of dredging intensity is given in the associated paper in this journal by NEWELL *et al.* (2002).

Summary

We have shown that a small-scale operation at Licence Area 122/3 of some 150,000 tonnes per annum, even with intensive extraction rates per km^2, has a limited impact on the environment. The evidence suggests that, other than where sediments are physically disturbed by removal, physical resources are largely unaffected. There is some minor change in sediment characteristics. As reported in the accompanying paper by NEWELL *et al.* (2002), benthic biological resources would appear to be able to cope with the stresses induced by the minor change in sediment type, and indeed appear to benefit by the increased food resource provided by disturbance of the sediments.

What is also clear is that the development of a linear downtide extension to the nearbed, or benthic boundary, sediment plume provides a mechanism for potential extension of the impact well beyond the zone of extraction. This effect, apparently not significantly present on the North Nab 122/3 site, may be expected to be more significant for those areas where screening of cargoes takes place, and is suggested by the results of our studies on the Owers Bank, those of DICKSON and REES (1998) and anecdotal evidence from monitoring surveys of licences where screening is commonplace. More importantly, this may hold especially true for those deeper water communities (40 metres or so), less exposed to and tolerant of natural disturbances to the sedimentary regime (NEWELL *et al.*, 2002).

It is stressed that 'scaling up' of the results recorded so far from the comparatively shallow water small scale operations reported here to deeper water and more extensive operations with screening of cargoes is not a realistic option and should be avoided. Fundamental baseline data collection at these deep-water sites is required to understand the response signatures of the benthic communities to disturbances, both natural and anthropogenic, and the extent of plume migration under the different phases of development and dispersion.

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